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VERTICAL STRUCTURE OF A MATURE TYPHOON

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ABSTRACT

Aerological observations made in a mature typhoon on August 31 and September 1, 1949, by the Central Meteorological Observatory, Tokyo, are given and time cross sections are constructed showing the distribution of temperature, potential temperature, pressure, and circulation acceleration. The vertical structure of the typhoon is discussed and the results compared with those previously given by Palmén and by Simpson.

The *Kitty** typhoon of August 27–September 2, 1949, was of great intensity, and the most destructive storm to visit Tokyo in recent years. Over 100 lives were lost as a result of the storm, and estimates of property damage run well over ¥ 15,000,000,000 (about $40,000,000).

On the night of August 31, approaching Tokyo from the south at the speed of about 50 km./hr., the storm center crossed the Kanto district about 30 to 50 km. west of the Central Meteorological Observatory (CMO). Table 1 shows the central pressure, the track, and the velocity of movement of the *Kitty* typhoon, and table 2 the records of meteorological conditions at Tokyo (CMO) during its passage.

Observation of the *Kitty* typhoon was distinguished by at least the following two interesting features: (a) The storm center crossed the land a short distance west of Tokyo, where the net of meteorological observations is fairly dense. (b) It is fortunate that a good number of radiosonde and wind observations were successfully obtained from the storm area. A number of regular and special radiosonde releases were made at stations (CMO, Haneda Weather Central, and Aerological Observatory at Tateno) under the influence of this typhoon. Radiosonde flights and rawin observations for the *Kitty* typhoon made by the staff of CMO are given in tables 3 and 4. These observations, which include a radiosonde flight made at Tokyo near the core of the typhoon shortly in advance of the center, have made it possible to construct a more complete picture of the vertical structure of a typhoon in a *mature* stage of development than has been possible before.

*Name given the typhoon for purpose of identification in advisories.

TABLE 1.—*Track, central pressure and movement of the Kitty typhoon Aug. 28–Sept. 1, 1949*

Date and hour (135th meridian civil time)	Central pressure (estimated) mb.	Locus of center		Movement of center	
		Latitude ° N	Longitude ° E	Direction	Speed km/hr
Aug. 28, 09h	980	23.2	154.5	NW	20
15	980	24.2	153.7	NW	20
21	980	25.0	152.8	NW	25
Aug. 29, 03h	980	25.8	151.8	NW	25
09	980	26.7	150.7	WNW	25
15	980	27.3	149.4	WNW	25
21	980	27.8	148.0	WNW	25
Aug. 30, 03h	980	28.4	146.5	WNW	25
09	980	29.0	145.1	WNW	25
15	970	29.6	143.6	WNW–NW	28
21	970	30.3	142.2	NW	28
Aug. 31, 00h	960	30.8	141.7	NW	30
03	960	31.5	141.0	NW	30
06	960	32.2	140.3	NW	30
09	950	32.7	139.9	NW	30
12	950	33.5	139.5	NW	25
13	950	33.6	139.4	NW	25
14	950	33.8	139.2	NW	25
15	950	34.1	139.0	NW–NNW	25
16	950	34.3	138.9	N	20
17	950	34.4	139.0	NNE	25
18	955	34.7	139.2	N	40
19	960	35.2	139.2	N	55
20	965	35.7	139.2	N	55
21	975	36.2	139.1	N	55
22	975	36.6	139.0	NNW	55
23	980	37.2	138.6	NNW	55
Sept. 1, 00h	980	37.6	138.4	N	50
01	980	37.9	138.5	N–NNE	50
03	980	38.8	138.7	NNE	50
06	980	40.3	139.0	NNE	50
09	985	41.5	140.0	NNE	50

Many papers concerning the vertical structure of the *Kitty* typhoon have been published under several titles [1, 2, 3, 4]. The following note attempts to summarize the salient features of the storm, obtained from all available sources of information, as a possible contribution to future studies of typhoon structure and to compare them with the picture of the vertical structure of tropical cyclones as previously given by Palmén [5], and Simpson [6].

TABLE 2.—*Meteorological observations at Tokyo (CMO), Aug. 31–Sept. 1, 1949*

Date and hour (135th meridian civil time)	Pressure (sea level) mb.	Temp. °C.	Humidity %	Wind direction	Wind speed m/sec.
Aug. 30, 24h	1011.5	25.0	94	NE	3.6
Aug. 31, 01h	1010.7	25.1	94	NE	3.4
02	1010.0	25.1	93	NE	4.4
03	1009.2	25.1	92	NE	3.4
04	1008.8	24.9	93	NE	4.4
05	1008.3	25.0	92	NE	5.4
06	1007.8	25.0	94	NE	5.5
07	1007.1	25.9	90	NE	7.6
08	1006.3	26.5	87	ENE	7.1
09	1005.2	26.6	86	ENE	8.2
10	1004.3	26.7	89	ENE	9.6
11	1002.8	27.5	81	ENE	10.1
12	1001.2	26.5	87	NE	11.5
13	999.9	26.1	88	E	12.7
14	997.8	25.9	90	E	13.7
15	996.8	25.7	90	E	14.2
16	995.0	25.6	90	ESE	18.0
17	993.0	25.7	89	ESE	17.1
18	989.5	25.4	88	E	17.6
19	986.4	24.9	86	ESE	20.2
20	986.6	24.2	91	E	19.4
21	988.7	23.6	95	SSE	22.2
22	991.6	23.5	96	S	21.6
23	994.4	24.4	93	S	22.8
24	998.0	24.7	93	S	15.5
Sept. 1, 01h	999.6	25.1	90	S	15.8
02	1002.2	25.6	88	S	12.4
03	1003.2	25.2	89	S	13.7
04	1003.8	25.5	88	S	11.7
05	1004.8	25.8	88	S	10.3
06	1005.9	25.3	88	S	9.1
07	1006.7	25.1	92	S	7.1
08	1007.5	25.2	91	S	8.5
09	1008.0	25.9	89	S	7.4
10	1008.6	26.3	88	SSE	7.6
11	1008.6	26.7	84	SSE	8.9
12	1008.6	27.5	78	SSE	8.5
13	1008.6	28.3	74	SSE	8.2
14	1008.4	27.5	79	SSE	9.4
15	1008.8	26.3	84	SSE	8.7
16	1009.0	26.1	86	SSE	6.5
17	1008.8	26.0	85	SSE	8.7
18	1009.8	25.6	88	SSE	7.4
19	1010.6	25.6	90	SSE	7.4
20	1011.1	25.3	90	SSE	3.6
21	1011.5	25.0	90	S	5.7
22	1011.6	24.6	91	S	5.9
23	1011.4	24.5	90	S	4.2
24	1011.3	24.3	90	S	3.6

Figure 1 is the time cross section showing the distribution of temperature (broken lines) and potential temperature (solid lines). It would appear that the core of the storm is decidedly warmer, especially at higher levels, than the air columns at 200 km. in the front and 300 km. in the rear from the center. And it would also appear that the core of the storm is decidedly higher in potential temperature, especially at higher levels. These two features are quite similar to Palmén's cross section [5], which shows that there is a marked descending motion in the free atmosphere in the core of the storm. It would appear that the storm region in the front and the rear of the core is decidedly colder both in air temperature and potential temperature, especially at higher levels, than the air columns at great distance from the center. The very heavy lines with considerable slope show the boundary surfaces separating two regions of ascending and descending air currents. This is quite *different* from Palmén's cross section. In the stormy region of any tropical storm in a mature stage of development there *must* be an intense ascending motion, which results in dynamical cooling and the uprush of the isentropic surface. So the vertical structure given for the *Kitty* typhoon seems to be more natural as well as more trustworthy than Palmén's cross section for the Miami-New Orleans hurricane of September 17–21, 1947.

If we suppose that the time cross section of the *Kitty* typhoon takes over the role of the *spatial* meridional cross section of the *Kitty* typhoon, we can reach some important conclusions. In view of the importance of baroclinicy

TABLE 3.—*Radiosonde observations by the Central Meteorological Observatory, Aug. 30–Sept. 1, 1949*

Release date and hour (135th meridian civil time)	Aug. 30, 1230			Aug. 31, 0904			Aug. 31, 1220			Aug. 31, 1330			Aug. 31, 1554			Aug. 31, 1849			Sept. 1, 0150			Sept. 1, 1100		
Height km.	Pressure mb.	Temperature °C.	Humidity %	Pressure mb.	Temperature °C.	Humidity %	Pressure mb.	Temperature °C.	Humidity %	Pressure mb.	Temperature °C.	Humidity %	Pressure mb.	Temperature °C.	Humidity %	Pressure mb.	Temperature °C.	Humidity %	Pressure mb.	Temperature °C.	Humidity %	Pressure mb.	Temperature °C.	Humidity %
0.5	957	25.7	59	953	22.8	91	948	22.4	96	948	23.3	94	944	23.1	92	935	22.1	90	947	22.8	93	955	23.1	97
1.0	904	21.4	68	899	20.5	87	895	20.8	96	895	20.7	97	891	20.7	92	881	18.8	94	893	20.5	87	901	20.4	87
1.5	853	18.6	71	848	18.4	86	844	17.4	96	844	18.0	98	840	17.8	92	832	16.2	97	843	17.6	86	849	18.3	75
2.0	804	16.7	66	803	16.0	84	796	15.8	96	796	15.9	98	792	15.2	90	784	14.4	92	795	16.4	79	801	16.9	73
3.0	715	13.0	53	711	11.5	77	707	10.5	96	707	10.5	99	704	10.8	86	696	10.6	89	705	12.7	63	712	13.1	65
4.0	633	7.4	37	629	7.2	76	627	6.2	96	627	7.7	100	623	5.5	86	616	6.1	81	625	5.5	75	632	6.5	74
5.0	560	1.6	29	556	1.8	70	553	0.1	96	555	2.8	100	551	0.9	86	545	1.5	88	552	−1.1	88	559	1.9	86
6.0	495	−3.5	25	491	−3.1	50							485	−4.6	85	481	−2.9	88	487	−5.0	91	493	−2.5	65
7.0	435	−9.1	21	432	−7.8	42							427	−10.9	77	424	−7.3	80	428	−9.4	88	433	−8.5	70
8.0	383	−14.6	20	380	−13.5	42							375	−14.9	69	372	−12.4	80	376	−13.5	86	381	−12.7	70
9.0	335	−21.1	20	332	−18.4	42							327	−21.4	68	325	−17.0	79	329	−19.2	85	333	−19.8	70
10.0	292	−29.3	18	289	−23.4	39							285	−28.2		285	−23.6	74	287	−26.2	83	291	−27.7	
11.0	253	−35.1		252	−29.3	38							248	−36.3		248	−28.7		249	−33.5		253	−33.9	
12.0	219	−41.8		219	−35.3								213	−43.3		216	−36.1		217	−42.0		219	−39.5	
13.0	188	−49.6		189	−44.2								184	−50.4		185	−42.7		187	−48.3		188	−44.1	
14.0	161	−58.6		163	−50.2								157	−58.0		159	−50.3		160	−56.8		163	−48.7	
15.0	137	−65.0		139	−59.3								135	−65.5		136	−56.4		136	−62.5		139	−53.4	
16.0				119	−66.0								112	−72.9		116	−63.9		115	−69.3		119	−59.3	
17.0				100	−66.8								96	−77.2		97	−69.0					101	−62.9	
18.0				85	−65.3								84	−73.0		83	−69.8					85	−62.2	
19.0				72	−63.4								68	−71.2		69	−70.0					73	−61.5	
20.0				61	−59.8																	63	−58.0	
21.0				52	−54.7																	53	−54.7	
22.0				45	−49.7																	45	−52.6	
Maximum height (m.)	15,479			24,697			5,019			5,587			19,097			19,377			16,902			22,036		
Remarks																The release was made shortly in advance of the core								

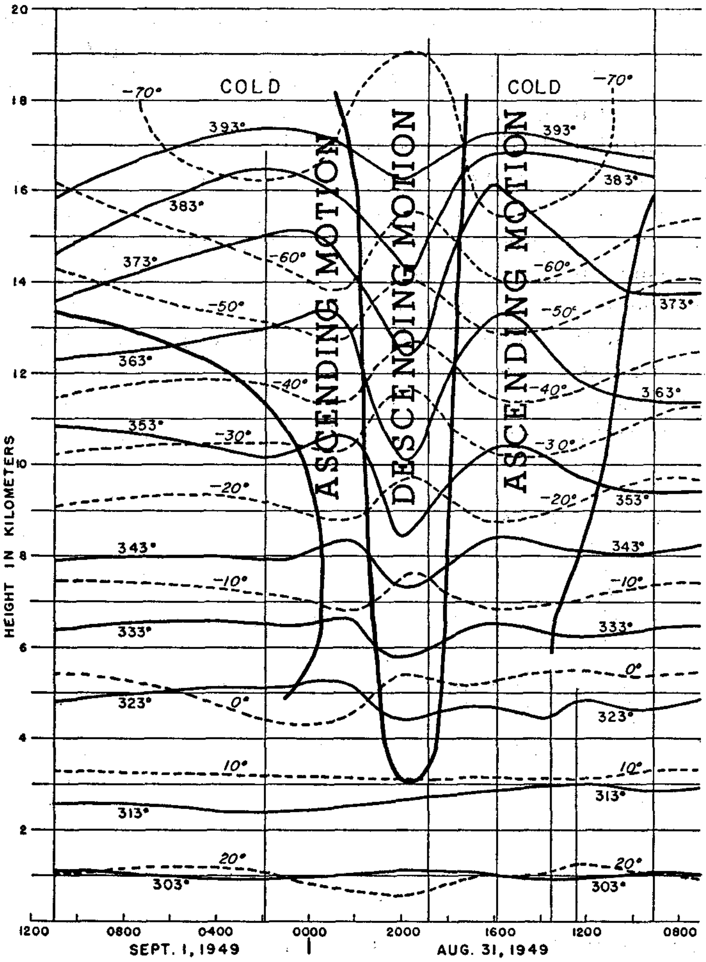

FIGURE 1.—Time cross section of the *Kitty* typhoon showing temperature (° C.) (broken lines) and potential temperature (° A.) (solid lines). The heavy solid lines with considerable slope separate two regions of ascending and descending air currents.

for the dynamics of a typhoon, the present author intends to evaluate the variation of the circulation with time, $\frac{dC}{dt}=-\oint\frac{dp}{\rho}$, where ρ is the density, p the atmospheric pressure. If the circulation in a vertical plane is to be computed, a convenient path of integration would consist of two isobars and two vertical lines connecting these isobars. In order to compute the intensity of the circulation acceleration in the cross section of the *Kitty* typhoon, one might choose the principal isobars p_l and p_{l-100} and the verticals a_s and a_{s+1} connecting these isobars at two successive soundings (fig. 2). Integration along the isobars gives zero. From the hydrostatic equation, it follows that $-\frac{dp}{\rho}=gdz=d\psi$, where g is the acceleration of gravity, z the height, and ψ the geopotential. Thus, along the curves a_s and a_{s+1} the height differences between two successive principal isobars may be integrated so that $\frac{dC}{dt}=\psi_s-\psi_{s+1}$. The circulation acceleration is directed as indicated by the arrows in figure 2. Thus the circulation is upward toward lower pressure on the warmer side, downward toward higher pressure on the colder side, and from the colder to the warmer side along the higher pressure surface, and back from the warmer to the colder side along the lower pressure surface.

To evaluate the circulation acceleration, the isobars for every 100 mb. and the lines indicating the release time may be drawn in the cross section of the *Kitty* typhoon. The evaluated height differences are tabulated in figure 3, where the circulation acceleration in the direction indicated by the arrows in figure 2 is taken to be positive. The circulation accelerations are written for

TABLE 4.—*Rawin observations by the Central Meteorological Observatory, Aug. 31–Sept. 1, 1949 (135th meridian civil time)*

Aug. 31, 0920			Aug. 31, 1220			Aug. 31, 1656			Aug. 31, 1840			Sept. 1, 1225		
Height m.	Direction degrees	Speed m/sec.	Height m.	Direction degrees	Speed m/sec.	Height m.	Direction degrees	Speed m/sec.	Height m.	Direction degrees	Speed m/sec.	Height m.	Direction degrees	Speed m/sec.
400	71	6.2	300	93	11.0	2000	166	9.0	370	110	7.9	350	196	8.0
800	97	13.0	600	87	14.0	2300	117	6.5	750	112	10.8	800	193	12.0
1050	109	12.5	900	90	18.0	2600	114	6.8	1100	124	11.0	1250	211	13.0
1350	119	9.5	1150	97	12.0	2900	173	7.8	1480	126	14.8	1700	217	14.0
1600	126	8.0	1400	115	11.0	3300	146	8.2	1830	136	13.4	2200	229	15.5
1850	126	5.5	1650	151	5.8	3700	149	6.5	2250	136	15.8	2700	232	12.5
2100	131	5.0	1900	180	7.5	4100	187	5.3	2550	141	13.5	3150	246	10.0
2350	118	7.2	2150	200	7.3	4550	187	8.2	2950	130	18.5	3600	259	8.5
2700	111	10.3	2400	239	8.6	4950	170	8.6	------	-------	----	4100	264	6.5
3100	108	14.5	2650	262	5.0	5400	161	8.8	------	-------	----	4600	275	6.0
3900	110	27.5	2900	260	4.5	5900	160	9.0	------	-------	----	5050	284	6.0
4800	106	47.5	3150	216	5.0	6300	150	7.8	------	-------	----	5500	269	6.5
5300	99	35.0	3400	180	2.8	6700	150	7.2	------	-------	----	6000	287	7.5
5750	103	52.0	3650	157	5.4	7100	161	7.2	------	-------	----	6450	304	7.0
6100	92	42.0	3900	143	6.9	7450	175	7.0	------	-------	----	6900	336	5.8
6400	87	29.0	4150	142	8.3	7850	149	6.5	------	-------	----	7400	315	4.5
6700	79	26.0	4400	142	9.3	8200	110	3.0	------	-------	----	7900	275	4.5
7000	69	21.0	4700	136	13.0	8600	110	9.3	------	-------	----	8350	237	10.5
7300	78	18.0	4950	135	11.5	9000	98	11.0	------	-------	----	8800	218	8.0
7550	99	11.0	5200	135	15.0	9400	119	14.0	------	-------	----	9300	200	7.0
7850	126	11.0	5400	126	17.0	9800	122	16.0	------	-------	----	9800	184	9.0
8150	160	14.0	5650	135	13.2	10250	106	18.0	------	-------	----	10200	160	10.2
8450	165	14.0	------	-------	----	10700	95	11.5	------	-------	----	10700	182	10.4
8750	165	19.0	------	-------	----	11150	111	18.5	------	-------	----	11200	200	10.0
9050	108	12.0	------	-------	----	11650	106	22.2	------	-------	----	11700	214	7.8
9400	100	17.0	------	-------	----	12100	101	25.0	------	-------	----	12100	181	5.5
9700	101	13.0	------	-------	----	------	-------	----	------	-------	----	12600	271	9.5
10050	102	17.0	------	-------	----	------	-------	----	------	-------	----	13100	238	6.8
10400	154	25.0	------	-------	----	------	-------	----	------	-------	----	13600	254	6.5
10800	214	38.0	------	-------	----	------	-------	----	------	-------	----	------	-------	----
11150	222	37.0	------	-------	----	------	-------	----	------	-------	----	------	-------	----
11550	232	51.0	------	-------	----	------	-------	----	------	-------	----	------	-------	----
12000	270	69.0	------	-------	----	------	-------	----	------	-------	----	------	-------	----
12400	265	63.0	------	-------	----	------	-------	----	------	-------	----	------	-------	----
12900	262	41.0	------	-------	----	------	-------	----	------	-------	----	------	-------	----
13450	262	42.0	------	-------	----	------	-------	----	------	-------	----	------	-------	----

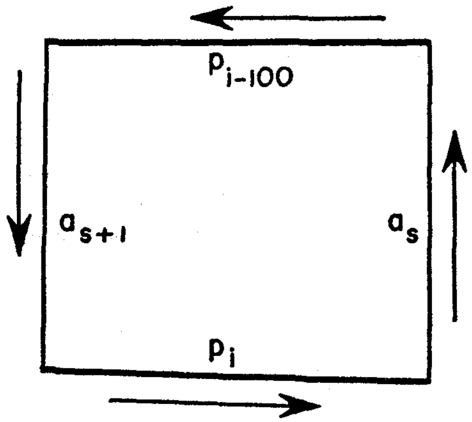

FIGURE 2.—Path of integration used in computing circulation acceleration. Circulation acceleration in the direction indicated by the arrows is taken to be positive.

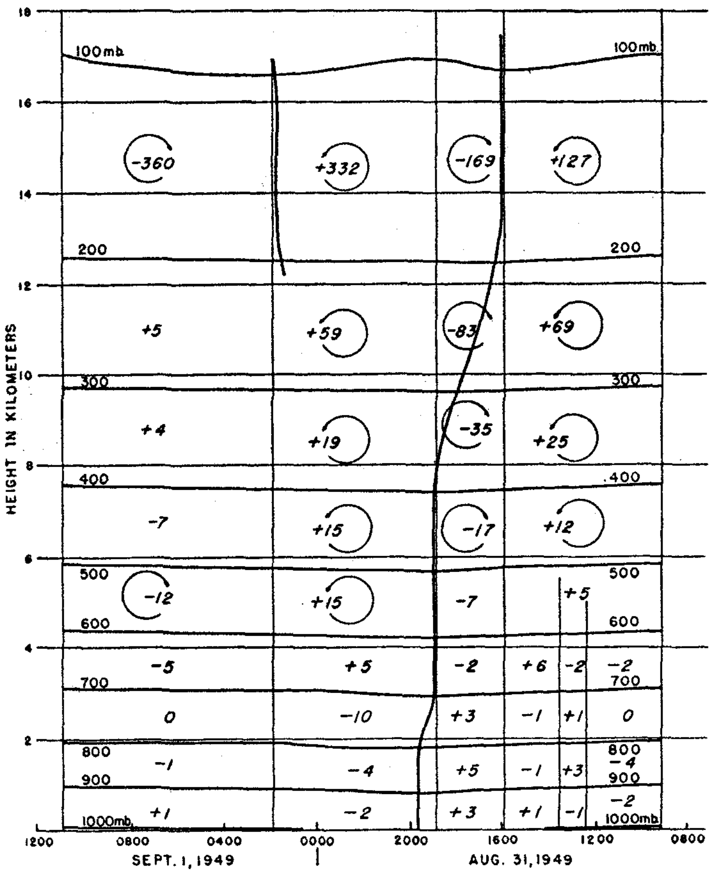

FIGURE 3.—Time cross section of the *Kitty* typhoon showing isobars (solid lines) and computed circulation accelerations. The number in each block formed by isobars and the thin vertical lines (times of release) is the circulation acceleration in meters. Blocks with circulation acceleration stronger than ±g·10m are designated by circular arcs, with arrow heads showing direction. The two heavy solid lines with considerable slope are the axes of low pressure.

each block in meters (geometrical height) instead of dynamic meters (geopotential). The descending motion in the core and the ascending motion in the storm region, must receive a retardation owing to the evaluated circulation acceleration, while the original baroclinicy loses its intensity. Thus the descending motion in the core and the ascending motion in the storm region are of *dynamic origin, other than the circulation acceleration.* The isobaric curves of figure 3 (and also table 5) show clearly that the amplitude of the pressure minimum is progressively decreased with increasing altitude in the troposphere. Above 12 to 13 km., such a tendency continues so that a maximum of pressure appears over the region of minimum pressure in the lower layers. The forward displacement of the pressure minimum at greater heights found by Simpson [6] seems to be real, and is largely a reversal from results of statistical investigations [7, 8] for extra-tropical cyclones. The heights of isobaric surfaces for each 100-mb. interval from the original soundings are printed in table 5.

TABLE 5.—*Heights for each principal isobaric surface in meters*

Date and hour (135th meridian civil time)	Aug. 31st					Sept. 1st	
	0904	1220	1330	1554	1849	0150	1100
1000 mb.	76	32	6	−4	*−74*	15	76
900	989	947	922	911	*838*	929	989
800	1993	1955	1927	1917	*1839*	1934	1995
700	3113	3075	3046	3037	*2956*	3061	3122
600	4381	4345	4318	4303	*4224*	4324	4390
500	5846	----	----	5763	*5691*	5776	5854
400	7589	----	----	7494	*7439*	7509	7594
300	9752	----	----	9632	*9612*	9663	9744
200	12628	----	----	*12439*	*12502*	*12494*	12570
100	17018	----	----	*16702*	*16934*	*16594*	17030

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